

Feasibility of a Concrete Pavement Continuously Reinforced by Glass Fiber Reinforced Polymer Bars

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Abstract

One unique benefit of glass fiber reinforced polymer (GFRP) bar reinforcement is its electromagnetic transparency. This characteristic is useful for pavements supporting automated toll collection booths employing electromagnetic vehicle detectors. Engineers at the Texas Department of Transportation performed a detailed study of the viability of GFRP reinforcing bars in continuously reinforced concrete pavements (CRCP) at toll plazas. Due to a design requirement for “superior ride quality” engineers wanted to utilize CRCP rather than construct a jointed pavement using GFRP dowels, whose steel reinforced counterpart had not historically performed in terms of ride quality.

The authors’ design utilized an analytical method based on a simple mechanical model. The design was then verified using the computer program CRCP10, employing a 2-D finite element analysis. Both approaches accounted for the low modulus of elasticity (1/5 that of steel) and unique bond-slip stiffness of GFRP bars, characteristics critical to the design and behavior of the CRCP. Results indicate that a CRCP using GFRP can have performance similar to CRCP reinforced with steel, if the correct amount of reinforcement is provided. If not enough reinforcement is provided calculated cracks widths are excessive. If too much reinforcement is provided predicted cracks are too closely spaced, increasing the likelihood of punch out failures.

Keywords: GFRP, FRP, CRCP, concrete, pavement, electromagnetic, toll, JCP

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1.0 Introduction

Texas, like many other infrastructure owners in the United States, is pursuing creative ways to fund and develop new and increased capacity highway systems. Traditional highway funding through the fuel tax is not keeping up with demand at current tax rates and reimbursement formulas. In the current and foreseeable political climate increases in gasoline tax rates are unlikely. Therefore, in order to fund and expedite the development of critical transportation projects needed to reduce congestion in urban areas, Texas is turning to bond financed projects with bond payback formulas tied to toll collection.

1.1 The Challenge

An important facet to making tolled roadways successful is the utilization of automated toll collection. Using electronic, automated toll collection rather than traditional “throw as you go” systems reduces the bottleneck effect of tolling on the flow of vehicular traffic. However, some of the technology that is used to detect, characterize, and electronically toll vehicles, requires that the underlying roadway not contain material that could transmit or induct an electrical current which would thereby interfere with the vehicle imaging loops embedded in the roadway surface. The loop detectors used for toll collection are more complicated and much more sensitive than common loop detectors used for traffic signal activation. Thus pavements in the region of automated toll collection facilities must be electromagnetically transparent, which is not the case when using conventional steel reinforced concrete pavements.

Because drivers will be paying for these tolled roadways each time they use them, it is important that these facilities provide service above and beyond what is expected from a conventionally funded roadway. One of the most important aspects of a roadway that is readily apparent to users is ride smoothness, or lack thereof. Thus, an important design requirement is that the pavement provides superior ride quality, even at locations where the tolls are being collected. To this end, in the very first tolled highway projects to be built in the Texas Department of Transportation's (TxDOT) Austin District (the Loop 1 North Extension and the S.H. 45 North projects, known together as the “Big T”) engineers decided, in the highway design phase, to employ continuously reinforced concrete pavement (CRCP) throughout the projects, including the toll plaza areas. This would minimize closures associated with maintenance of flexible pavement, and of the two types of rigid pavement, CRCP has historically performed better than jointed pavements. The Texas Department of Transportation's (TxDOT) policy therefore, is to use CRCP for rigid pavements in Texas [1].

1.2 The Solution

For the “Big T” project, the issue of which pavement type to use had already been addressed by the requirement for superior ride quality. The question of how to provide the requisite electromagnetic transparency remained. Using fiber reinforced polymer (FRP) bars in place of steel reinforcement seemed to be the most reasonable solution. Such reinforcement has not yet been used in an actual CRCP though one such use was scheduled by the Virginia DOT until funding fell through [2]. Nonetheless, TxDOT engineers selected glass fiber reinforced polymer (GFRP) reinforcing bars to meet the electromagnetic transparency design constraint for several reasons, the primary perhaps being that carbon and aramid fiber reinforcing bars are prohibitively expensive. Other reasons include the availability of GFRP reinforcing bars, and familiarity with GFRP bars within the Department. GFRP bars have been used in several TxDOT sponsored research and testing projects related to the construction of the Sierrita de la Cruz Creek Bridge built in Amarillo, TX [3, 4, 5, 6, 7, 8].

2.0 GFRP Properties

While GFRP bars were chosen because their electromagnetic properties differed from those of steel bars, there are several other significant differences between the mechanical properties of GFRP and steel that must be considered in the design of reinforced concrete, such as CRCP. While bars with a variety of mechanical properties are available, depending on the manufacturing process, the glass fiber sizing, the chemical make up of the resin, and the surface treatment employed to facilitate bond development between the bar and surrounding concrete, the Department's current specifications for GFRP reinforcing bars require that the reinforcing bars have the following properties:

Table 1 - Specified GFRP Reinforcing Bar Properties

GFRP Properties:		
Tensile Modulus of Elasticity, E_{FRP}	40817 MPa	(5920 ksi)
Nominal Bar Diameter, d_b (#8 bar)	25.4 mm	(1.0 in)
Nominal Bar Diameter, d_b (#6 bar)	19.1 mm	(0.75 in)
Guaranteed tensile strength, f_{fu}^* (#8 bar)	551.6 MPa	(80 ksi)
Guaranteed tensile strength, f_{fu}^* (#6 bar)	620.5 MPa	(90 ksi)
Minimum Ultimate Bond Stress, τ (27.6 MPa (4000 psi) concrete)	7584 kPa	(1100 psi)

Additionally, the special specification requires that all GFRP reinforcement be comprised of braided or woven continuous glass fibers impregnated with and bound by a vinyl ester resin matrix through a pultrusion manufacturing process as approved by the Engineer.

3.0 CRCP Behavior

CRCP, and rigid pavements in general, act like a footing and distribute concentrated wheel loads to a much larger area of the less stiff subgrade. This reduces the stresses and the strains on the subgrade. In addition to the wheel loads applied to the pavement, CRCP is subject to shrinkage and temperature strains which force the concrete to crack. The reinforcement in the concrete is intended to keep these cracks to a sufficiently small width such that aggregate interlock can be maintained to transfer wheel loads across the cracks. In a jointed pavement cracks are induced at set distances by saw cutting or otherwise providing partial depth joints in the concrete where relatively wide cracks will then form. Because the cracks are wide, aggregate interlock is not maintained, and the shear induced by wheel loads must be transferred across the joint by the doweling action of large dowel rods.

For fiber reinforced polymers, the strength and stiffness are provided by the fibers, a majority of which are oriented in the longitudinal direction. This means that fiber reinforced polymers are typically much weaker in shear, and as such are not ideal for use as dowel bars, which only transmit loads across the joint via shear on the bar. Nevertheless, FRP dowel bars have been used in jointed pavements in Ohio and other northern states in the US with mixed results.

The cracking pattern that develops, in terms of the crack spacing, and crack widths, in CRCP is a function of the mechanical properties of the reinforcement and the concrete, and the friction between the pavement and the subgrade. As the concrete pavement shrinks, that contraction is

resisted by the reinforcement and the subgrade induced friction. The concrete develops tensile stresses until it reaches or exceeds its tensile capacity and a crack forms at the weakest point in this section of the pavement. Tension in the concrete near the crack is thereby relieved, and a tensile force is developed in the reinforcement at the crack, as shown in Figure 1. This continues until several cracks have developed and the tensile force in the concrete is no longer enough to result in additional cracks.

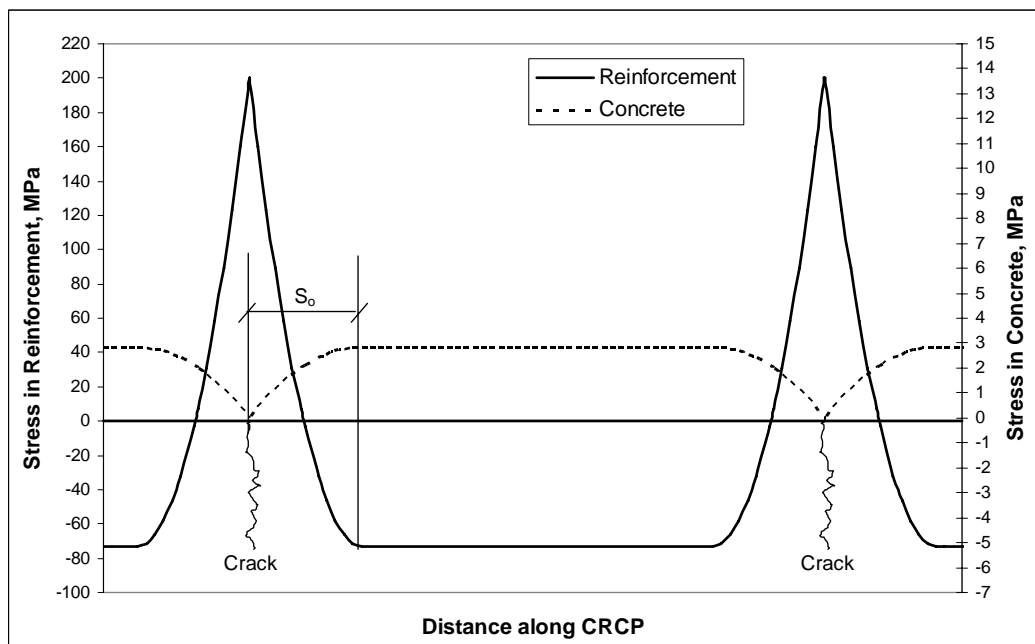


Figure 1 - Stresses in Concrete and Reinforcement in Cracked CRCP Due to Shrinkage and Temperature Effects

3.1 CRCP and GFRP Bar Design Limits

When determining the reinforcement pattern for CRCP there are three limits that need to be checked; crack width, crack spacing, and stress in the reinforcement. The limit on the crack width is required to ensure aggregate interlock is maintained along that crack to enable force transfer. The "AASHTO Guide for the Design of Pavement Structures" [9] limits the crack width to 1.02 mm (0.04 in), however, research performed at the University of Texas determined that this may be excessive and recommended a maximum value of 0.58 mm (0.023 in) [10, 11]. The relationship between crack spacing and crack width is such that when there are a lot of cracks per a given distance the cracks will be smaller. This gives an upper limit for crack spacing, which is typically about 2.4 m (8.0 ft). There is also a lower limit on crack spacing. If cracks are spaced too close together, punch out failures can occur, where a small area of concrete is broken away and pushed down into the subgrade. The lower limit published in the AASHTO Pavement Design Guide is 1.1 m (3.5 ft) [9]. Stress in the reinforcement must be limited to ensure that the reinforcement does not undergo any plastic deformation. With steel bars that limit is 75% of the yield strength [9]. GFRP bars are linearly elastic to failure and so do not yield. For a given bar grade, the guaranteed tensile strength, f_{fu}^* , is specified as the mean minus three times the standard deviation of the tensile strength of a set of tested samples. Since the internal concrete environment can further reduce the

tensile strength of the GFRP bars, the design tensile strength, f_{fu} , is equal to f_{fu}^* times a C_E factor of 0.7, per ACI 440.1R-03 "Guide for the Design and Construction of Concrete Reinforced with FRP Bars" [12].

The governing limit for stress in the reinforcement for GFRP reinforced concrete pavement could be that of creep rupture, particularly since a portion of the environmental loading will be a sustained load. When FRP reinforcing bars are subjected to a sustained load beyond a threshold amount, the bars can creep over time to the point of rupture. This type of failure is referred to as creep rupture. GFRP bars are particularly susceptible to this sort of failure. Creep rupture is a complicated phenomenon as it is affected by temperature and environment. Additionally, there are no standardized creep tests for FRP bars, and as such results vary significantly. Because of this lack of agreement and definitive test results, a conservative limit of $0.2f_{fu}$ is published in ACI 440.1R-03. This limit is intended to represent the worse case scenario, encompass all probable design lives and environmental conditions, and include a factor of safety of 1.67 [12].

4.0 Analysis/Design

For the "Big T" project, after taking into consideration design traffic volume, design pavement life, concrete properties, subgrade quality, drainage, etc., TxDOT pavement engineers determined that a 27.9 cm (11 inch) thick CRCP is needed. The next step is to determine the reinforcement required. The analysis methods used must be able to take into account the difference in mechanical properties between steel and GFRP reinforcing bars. The most noteworthy mechanical properties affecting the behavior of CRCP are the modulus of elasticity of the GFRP bars, and the difference in bond-slip stiffness between GFRP and steel bars. Two different analysis methods are used so that their results can be compared.

Before any detailed calculations are performed on the proposed CRCP it is important to get a general idea of the results that are expected; and after performing the detailed calculations to review the results to determine if they are reasonable. To get an idea of what results are reasonable, consider the following two cases. First, consider the case where an equal area of GFRP bars is provided ($A_{FRP}=A_S$), as compared with the area of steel bars in the standard steel reinforced CRCP, and second, the case where an equivalent stiffness ($E_{FRP} A_{FRP}=E_S A_S$) is provided. In the former case we can guess that the crack spacing would be much greater in the GFRP reinforced pavement. This is because the stiffness of the steel resisting the concrete shrinkage, in conjunction with the friction of the subgrade, causes tension to develop in the concrete, which then cracks. If the same area of GFRP reinforcement, with roughly $1/5^{\text{th}}$ of the modulus of elasticity of steel, is provided, the tensile stresses introduced into the concrete by the reinforcement will be much less than in the steel reinforced CRCP. This would reduce the build up of tension in the slab delaying and minimizing the formation of cracks in the GFRP bar reinforced CRCP. When a crack does form, the stiffness of the bars resisting the widening of the crack is much less than for steel reinforced CRCP and therefore the crack opens much wider than does the crack in a steel reinforced CRCP. The net result is that cracks are spaced much further apart and are much larger in GFRP bar reinforced CRCP, versus equal area steel bar reinforced CRCP, which is undesirable. We can therefore conclude that we need to provide more cross-sectional area of GFRP than we would with steel.

Based on the line of reasoning above, that the stiffness of the steel causes the concrete to crack and keeps the cracks tight, it may be necessary to provide GFRP bars of equivalent stiffness to the steel bars in order to get the same crack pattern. If equivalent stiffness is provided, the concrete

theoretically would not “know the difference” between steel and GFRP in regions remote from the cracks. However, there is a significant difference in expected behavior in the vicinity of a crack. Since a much larger cross-sectional area of GFRP reinforcement is provided in the section the stress in the bars would be much less. Additionally, the surface area of the bond between the concrete and the bars would be significantly increased in an equivalent stiffness case due to the increased number of bars provided. The result of the lower stress in the bars and the increased bond surface area is that the tensile stress in the concrete develops much more rapidly as the distance from the crack increases. This increases the likelihood of having many, closely spaced cracks, because the concrete reaches its tensile strength limit much closer to a previously formed crack. This is problematic because closely spaced cracks are associated with punch-out failures.

The optimum amount of GFRP reinforcement is somewhere between that required to provide equal area and that required to provide equivalent stiffness to steel reinforced pavement. Since TxDOT uses a reinforcement ratio of 0.6% for CRCP reinforced with steel, and GFRP bars have roughly $1/5^{\text{th}}$ the modulus of steel bars, the optimum reinforcement ratio must be between 0.6% and 3.0%. Research performed at the University of Missouri, Rolla determined that the amount of GFRP reinforcement required to produce similar crack patterns to companion steel reinforced specimens in a fully restrained slab subjected to temperature and shrinkage deformations is three times the area of the steel reinforcement. This is based on a significant number of tests using restrained concrete panels subjected to shrinkage and temperature deformations and reinforced with either steel or GFRP [13].

4.1 Assumptions

Though many of the variables in the analyses were investigated over a range of possible values, the results shown below are based on the assumptions shown in Table 2.

Table 2 - Assumed Material Properties

Concrete Properties:		
Compressive Strength, f'_c	34.5 Mpa	(5000 psi)
Tensile Strength, f_t	3.0 Mpa	(434 psi)
Modulus of Elasticity, E_c	24849 Mpa	(3604 ksi)
Temperature and Shrinkage Strain, ϵ_s	-0.00074	
Subgrade Properties:		
Vertical Stiffness, k	108.6 MPa/m	(400 psi/in)
Bond-slip Stiffness	39.5 MPa/m	(145.5 psi/in)

4.2 Mechanical Model Analysis

This analysis follows a procedure developed by Gilbert [14]. The pavement is assumed to be a fully restrained member, which is an appropriate assumption for all locations except perhaps at the extreme ends of the slab. The effect of friction of the subgrade on the pavement is neglected in this analysis. This method allows for consideration of the modulus of elasticity of the GFRP. Gilbert's formula for the distance from the crack to where the stress in the reinforcement is fully transferred to the concrete, s_o in Figure 1, is an empirical formula based on steel reinforcement, and as such is not appropriate for use with GFRP reinforcement. Another formula, Equation 1, accounts for the bond properties of the GFRP bar and is thus used in this mechanical model analysis. This formula

is based on equations published by Comité Euro-International du Béton (CEB) [15]. A_c is the cross-sectional area of concrete per reinforcing bar. All other variables are as previously defined.

$$s_o = \frac{A_c \cdot f_t}{\tau \cdot \pi \cdot d_b} \quad (1)$$

The results of the mechanical model analyses are shown in Table 3. The results shown start with a reinforcement ratio of 0.01 at the top of the table and increase until the crack spacing limit is exceeded at a reinforcement ratio of 0.0179. Values underlined in the table exceed set limits and are therefore not acceptable. For comparison, an analysis of TxDOT's standard steel reinforced CRCP is included on the last line of the table.

The chosen design is shown in bold. This condition minimizes the amount of reinforcement required, while not exceeding any of the set limits. Knowing that the subgrade friction has been neglected, this design is also on the more conservative side, as including the effects of subgrade friction would decrease crack spacing, crack widths, and the required restraining force. A design that has predicted mean crack spacing closer to the upper bound would help to ensure that the effect of subgrade friction does not cause cracks to be too closely spaced. Other conditions were also considered in choosing this reinforcement pattern, such as the amount of space between bar bundles, and the preference for a single layer of reinforcement.

Table 3 - Mechanical Model Analysis Results

Bars	Spacing mm (in)	Reinforcement Ratio	Mean Crack Spacing m (ft)	Crack Width mm (in)	Stress in Reinforcement MPa (ksi)
2 ~ #6 GFRP	203 (8)	0.0100	<u>2.54</u> <u>(8.33)</u>	0.936 (0.037)	262.3 (38.0)
2 ~ #6 GFRP	178 (7)	0.0115	2.03 (6.67)	0.726 (0.029)	236.4 (34.3)
1 ~ #8 GFRP	152 (6)	0.0119	<u>2.54</u> <u>(8.33)</u>	0.894 (0.035)	231.2 (33.5)
2 ~ #6 GFRP	152 (6)	0.0134	1.52 (5.00)	0.542 (0.021)	203.5 (29.5)
2 ~ #6 GFRP	127 (5)	0.0161	1.09 (3.57)	0.383 (0.015)	171.2 (24.8)
4 ~ #6 GFRP	229 (9)	0.0179	<u>0.87</u> <u>(2.86)</u>	0.315 (0.012)	150.3 (21.8)
1 ~ #6 Steel	178 (7)	0.0057	1.69 (5.56)	0.655 (0.026)	<u>435.1</u> <u>(63.1)</u>

While these analyses predict stresses in the GFRP reinforcement in excess of the creep rupture limit discussed above, there are several reasons why this is acceptable. The stresses shown are the highest stresses in the reinforcement throughout the life of the pavement, meaning only a portion

of this stress will be sustained. The creep rupture limit is only applicable for sustained stresses. These analyses also neglect the additional restraint provided by the subgrade friction, which can significantly reduce the stress in the reinforcement. This can be seen by looking at the stress predicted for the steel reinforcement, which exceeds the yield strength of the steel. Yielding of the steel reinforcement has not been observed in actual installations of the commonly used steel reinforced CRCP. Additionally, the creep rupture limit is believed to be overly conservative, and the typical life of CRCP, 30 years, is not near as long as the required design life of typical concrete structures, upon which the creep rupture limit is based.

4.3 Finite Element Analysis

The designer performed several finite element analyses (FEA) of both steel and GFRP reinforced CRCP using computer software developed, tested, and validated through several TxDOT sponsored research projects conducted at the University of Texas at Austin. The program, CRCP10, uses a 2D FEA that accurately models the CRCP. The software employs a Monte Carlo simulation to predict probable ranges of crack spacing, which are more relevant than mean crack spacing since a pavement with acceptable mean crack spacing might also have some crack spacings that fall outside the AASHTO limits. CRCP10 allows the user to specify the modulus of elasticity of the reinforcement, use complex bond-slip stiffness relationships, and model subgrade friction.

The designer employed a similar approach to selecting the optimal design as was used for the mechanical model analyses, evaluating several designs to determine which would work best, however, only the results for the chosen design are presented herein. The designer performed a parametric sensitivity study of the effects of different variables on the predicted behavior of the CRCP. Variables such as the modulus of elasticity, coefficient of thermal expansion, and shrinkage of the concrete were investigated, as well as the subgrade friction, and the bond-slip stiffness of the reinforcement.

The bond-slip stiffness of the reinforcement has the greatest affect on the performance of the GFRP reinforced CRCP, while the other variables, within expected ranges, do not affect the pavement enough to deem the predicted performance unacceptable. A large amount of bond-slip stiffness test data exists due to the combined efforts of several universities participating in the International Round Robin tests for FRP reinforcement [8]. The data shows that the wide range of surface treatments available from a large number of manufacturers worldwide, results in a wide range of possible bond-slip stiffness values. Bond-slip stiffness values ranging from 23.07 MPa/mm (85,000 psi/in) to 135.72 MPa/mm (500,000 psi/in) have been observed, although the mean value is closer to 40.71 MPa/mm (150,000 psi/in). For comparison, a midrange value of bond-slip stiffness for steel reinforcement is 135.72 MPa/mm (500,000 psi/in). The wide variety of surface treatments available with steel reinforcement also gives a large range of possible bond-slip stiffness values for steel reinforcement. However, as shown in Table 4, the performance of the CRCP is not as sensitive to the bond-slip stiffness of steel reinforcement as it is with GFRP bars. Possible explanations for this include the increased area of bond between the reinforcement and the concrete when using GFRP bars, as well as the decreased modulus of elasticity of the GFRP bars, which results in higher reinforcement strain and hence more slip.

From the results in Table 4 it appears that lower bond-slip stiffness values result in better pavement performance in terms of mean crack spacing and punchout failures. A lower value of bond-slip stiffness for the GFRP bars is expected, as a majority of the test results for the GFRP bars had bond-slip stiffness values less than 54.38 MPa/mm (200,000 psi/in). Additionally, these

tests were performed on a single bar in concrete placed and cured under controlled laboratory conditions. In the case of the recommended design, a bundle of 2 bars is used, which will have bond-slip stiffness less than the combination of two single bars as assumed in the analyses. The analyses predict that the selected design will have acceptable performance equal to or better than that of steel for all reasonable ranges of material properties, thus making CRCP reinforced with GFRP a feasible means to provide electromagnetically transparent pavements. However, a full scale installation of such pavement is needed to prove that wide implementation will result in serviceable pavement in toll plazas of Texas tollways.

Table 4 - Finite Element Analyses Results

Bars	Spacing mm (in)	Bond-Slip Stiffness MPa/mm (psi/in)	Mean Crack Spacing m (ft)	Crack Spacing Standard Dev. m (ft)	Crack Width mm (in)	Stress in Reinforcement MPa (ksi)	Failures @ 100 Million ESALs /km (/mi)
2 ~ #6 GFRP	178 (7)	23.07 (85,000)	1.71 (5.60)	0.68 (2.23)	0.663 (0.026)	94.1 (13.7)	0.4 (0.7)
2 ~ #6 GFRP	178 (7)	54.29 (200,000)	1.15 (3.78)	0.47 (1.53)	0.478 (0.019)	84.0 (12.2)	15.5 (24.9)
2 ~ #6 GFRP	178 (7)	108.58 (400,000)	1.21 (3.96)	0.61 (2.00)	0.413 (0.016)	82.1 (11.9)	104.6 (168.3)
2 ~ #6 GFRP	178 (7)	135.72 (500,000)	0.97 (3.19)	0.69 (2.28)	0.362 (0.014)	73.9 (10.7)	206.0 (331.6)
1 ~ #6 Steel	178 (7)	81.43 (300,000)	1.11 (3.65)	0.42 (1.37)	0.386 (0.015)	223.7 (32.5)	3.4 (5.5)
1 ~ #6 Steel	178 (7)	141.15 (520,000)	0.92 (3.01)	0.45 (1.48)	0.369 (0.015)	235.7 (34.2)	29.8 (47.9)
1 ~ #6 Steel	178 (7)	190.01 (700,000)	0.84 (2.75)	0.37 (1.22)	0.344 (0.014)	233.6 (33.9)	39.2 (63.1)

5.0 Implementation

TxDOT engineers developed standard details for CRCP utilizing GFRP reinforcement to be used in central Texas toll projects. While GFRP reinforced CRCP standard sheets have been included in several let toll projects, they have not yet been implemented. For some projects, TxDOT pavement engineers have changed from the designed CRCP to a jointed concrete pavement (JCP) after the projects were let to contract because GFRP dowel bars have successfully been used for JCP in other states, while no direct empirical evidence of the behavior of CRCP with GFRP reinforcing exists. The JCP employs 457 mm (18 in.) long, 38 mm (1.5 in) diameter GFRP dowel bars, spaced at 229 mm (9 in). Transverse contraction joints are spaced at 4.6 m (15 ft), while the longitudinal joints are typically spaced at 3.7 m (12 ft), up to a maximum of 4.9 m (16 ft). Along the pavements longitudinal joints, 914 mm (36 in) long #6 GFRP reinforcement is provided at 406 mm (16 in.) spacing as transverse tie bars.

Recently, limits to the use of JCP for toll plaza applications have been identified, such as the inability to accommodate high speed loop detectors that cannot cross the required saw cut pavement joints. This proves to be problematic with JCP as transverse joints at relatively short

spacings, 4.6 m (15 ft), are required. Since CRCP is free of the problematic transverse joints, this JCP deficiency has again raised the possibility of implementing the CRCP with GFRP design discussed herein for certain toll road applications in Texas. Experimental validation of the mechanical and FEA models is still needed prior to implementation of the final design. Towards this end, TxDOT pavement engineers are considering building a test section of pavement in a non-critical location so that the design can be empirically verified.

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